Relaxometric Characterization of Human Cortical Bone

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Introduction:
Magnetic Resonance Imaging methods such as ultra-short echo time (uTE) imaging are capable of collecting proton signals from human cortical bone [1], which consists of collagen networks (osteoid), mineralized calcium phosphate microcrystals (hydroxyapatite), and porous channels (Haversian canals). In cortical bone, water exists in an ensemble of microenvironments and may be tightly bound to hydroxyapatite surfaces, loosely associated with the collagenous osteoid, or freely diffusing in the Haversian spaces. As such, the proton NMR signal arising from cortical bone may be best characterized by a distribution of relaxation components [2], potentially confounding uTE imaging and other NMR measurements that provide relaxation-based contrast. To this end, both \( T_1 \) and \( T_2 \) relaxation properties of human cortical bone are characterized herein to quantify multi-exponential relaxation and field dependence.

Methods:
A series of human cortical bone samples were harvested from femurs of healthy male and female donors. The samples were machined in PBS to 5x5x10mm dimensions to remove periosteum and endosteum layers, thus producing uniform cortical bone, which was blotted dry and immersed in Fomblin, a susceptibility-matched fluorocarbon oil with no proton NMR signal. To characterize multi-exponential \( T_1 \) and \( T_2 \) relaxation components and magnetic field strength dependencies, separate NMR experiments were performed at 0.5, 4.7, 7, and 9.4 T as follows: a CPMG pulse sequence with 100 µs echo spacing and 90°/180° hard pulses of approximately 7.5/15 µs was performed with 4000 echoes to measure \( T_2 \) relaxation characteristics; a single hard inversion pulse followed by a recovery period and subsequent CPMG sequence as above (IR-CPMG) provided two-dimensional \( T_1-T_2 \) measurements with the recovery period duration varied from 20 ms to 2.5 s; and IR-CPMG sequences with low-power (soft) inversion pulses yielded \( T_2 \)-\( T_1 \) measurements without fully inverting short-lived signals, probing magnetization transfer effects among relaxation components. CPMG echo magnitudes were fitted with a broad range of decaying exponential functions in a non-negative least-squares fitting to a range of decaying exponentials, producing a so-called \( T_1 \)-\( T_2 \) spectrum obtained from a hard IR-CPMG (Figure 3) exhibits two dominant components at approximately 100 µs and 500 µs, exhibited minor shifts between 0.5 and 4.7T main field strengths, indicating there is little field dependence in cortical bone transverse relaxation. The \( T_1-T_2 \)-\( T_2 \) spectrum obtained from a hard IR-CPMG (Figure 2), in which there is maximum simultaneous inversion of all proton pools, indicates that the shortest-lived \( T_2 \) component is best characterized with a \( T_1 \) of approximately 20 ms, while the majority of cortical bone water signal originates from proton pools with a \( T_2 \) of approximately 500 ms. However, the soft IR-CPMG \( T_1-T_2 \)-\( T_2 \) spectrum (Figure 3) exhibits two dominant \( T_2 \) components at 10 ms and 500 ms, both with a \( T_1 \) of 500 µs. Since the soft-IR preparation (150 µs pulse width) results in a relaxation-weighted inversion, the presence of the 10 ms \( T_2 \) component in Figure 3 indicates the cortical bone water compartments characterized by 100 µs and 500 µs are undergoing magnetization transfer. Results from CPMG and IR-CPMG \( T_1 \)-\( T_2 \) characterizations of human cortical bone water at 0.5T and the high fields of 4.7, 7, and 9.4 T will be presented, with emphasis on field-related changes to relaxation rates and apparent magnetization transfer.

Results and Discussion:
Human cortical bone exhibited a broad range of transverse relaxation time constants, approximately spanning 100 µs - 500 ms with the majority of \( T_2 \) spectral intensity falling below 1ms (Figure 1). Major \( T_2 \) spectral features, such as the two dominant components at approximately 100 µs and 500 µs, exhibited minor shifts between 0.5 and 4.7T main field strengths, indicating there is little field dependence in cortical bone transverse relaxation. The \( T_1-T_2 \)-\( T_2 \) spectrum (Figure 3) exhibits two dominant components at 10 ms and 500 ms, both with a \( T_1 \) of 500 µs. Since the soft-IR preparation (150 µs pulse width) results in a relaxation-weighted inversion, the presence of the 10 ms \( T_2 \) component in Figure 3 indicates the cortical bone water compartments characterized by 100 µs and 500 µs are undergoing magnetization transfer. Results from CPMG and IR-CPMG \( T_1 \)-\( T_2 \) characterizations of human cortical bone water at 0.5T and the high fields of 4.7, 7, and 9.4 T will be presented, with emphasis on field-related changes to relaxation rates and apparent magnetization transfer.

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